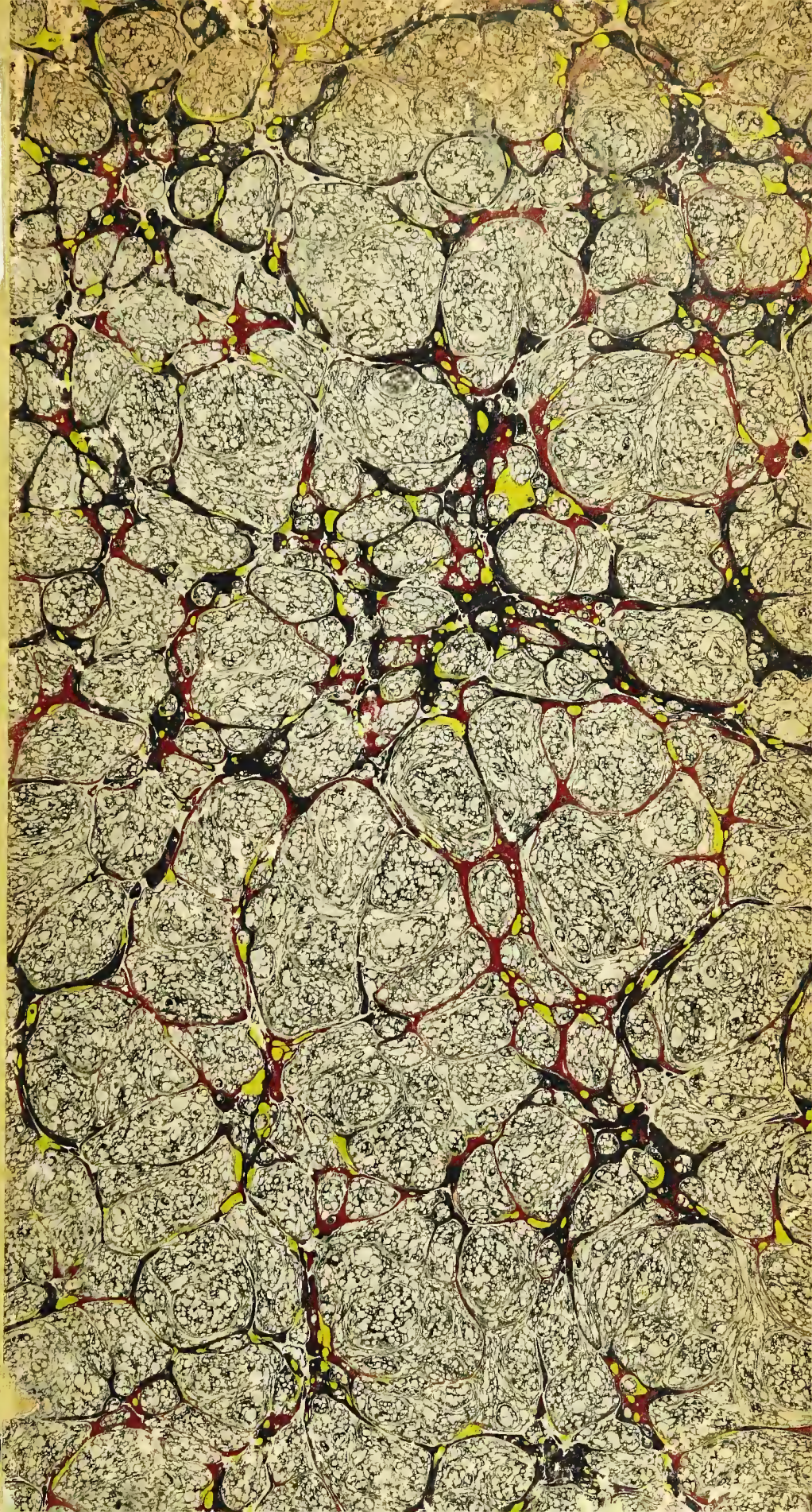


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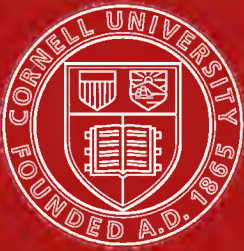
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The Tensile Strengths of the Copper-Zinc Alloys

A. THESIS

PRESENTED TO THE FACULTY OF THE GRADUATE
SCHOOL OF CORNELL UNIVERSITY FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

By JAMES MARTIN LOHR



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By JAMES MARTIN LOHR

THE TENSILE STRENGTH OF THE COPPER-ZINC ALLOYS¹

BY J. M. LOHR

The following investigation was undertaken for the purpose of establishing the relationship between the constitution of the copper-zinc alloys and their tensile strengths. For a long time such a series of data has been badly needed. Although brass has been used commercially for many years, it was only eight years ago that the equilibrium diagram was worked out, and it is not strange that, prior to that time, investigations on the various physical properties were made largely without any scientific basis as a guide for the work and for the interpretation of the results.

As early as 1842, Mallet² reported upon the specific gravities, color and character of fracture, tensile strengths, order of ductility, order of malleability, order of hardness and order of fusibility of the brasses. He used twenty-three pieces to cover the whole series, while only eleven of these covered the useful alloys. These alloys contained from about 47 to 100 percent copper, which are the percentages used in this work.

However, the most comprehensive work on this subject was that of the United States Board for Testing Materials, conducted by the Committee on Alloys under the chairmanship of Dr. R. H. Thurston.³ This work was very extensive, and hence no part of it could be studied in detail. Forty-two pieces were used in the series of tests, twenty-three of which cover the useful part of the series.

More recently, important researches have been made on the effects of heat treatment, the principal ones of which

¹ A paper read before the Eighth International Congress of Applied Chemistry in New York, September, 1912.

² Phil. Mag., [3] 21, 66 (1842).

³ Thurston: Materials of Engineering, Part 3.

are by Charpy,¹ Girard,² Cubillo,³ and Bengough and Hudson.⁴ In most cases, these have been intensive studies of alloys with definite compositions, rather than upon a series of different compositions.

The Equilibrium Diagram

In Fig. 1, the equilibrium diagram for the copper-zinc series is shown, as worked out by Shepherd,⁵ and recently very slightly modified by Carpenter and Edwards.⁶ The coördinates are temperatures and percentage composition. The various lines on the diagram show where certain chemical or physical changes take place. The upper heavy lines, or

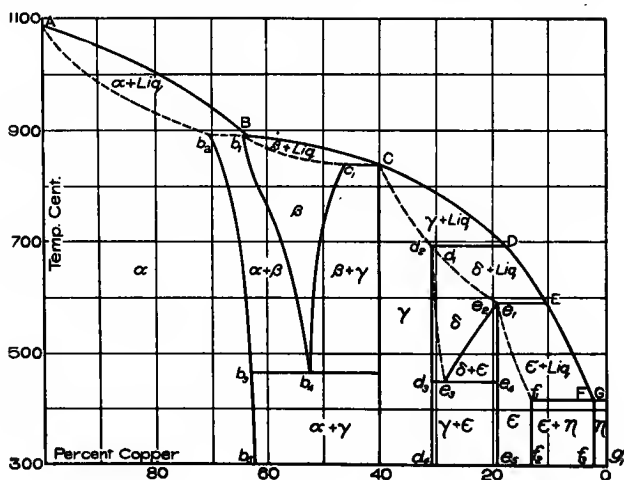


Fig. 1

liquidus, represent the temperatures above which the alloys are completely melted. The dotted lines or solidus, just below,

¹ Bulletin de la Société d'Encouragement de l'Étude des Alliages, page 1.

² Revue de Metallurgie, 1909; Mémoires, page 1069.

³ Proc. Inst. Mech. Eng., 791 (1905).

⁴ Jour. Soc. Chem. Ind., 27, 43, 654 (1908); Engineering, 90, 447 (1910).

⁵ Jour. Phys. Chem., 8, 421 (1904).

⁶ Engineering, 91, 200 (1911); 92, 431 (1912); Jour. Inst. Metals, 7, 70 (1912).

show the limits below which the alloys are completely solid. Between these lines crystals and melt co-exist.

In the diagram, the field marked a shows the concentration and temperatures over which pure crystals are stable under equilibrium conditions. These crystals are composed of a solid solution of zinc in copper, and show the same fern leaf-like structure throughout. Likewise, β , γ , δ , ϵ , and η show definite crystal forms in their respective fields as indicated. Also, as we pass from a to β we find a field b_1 , b_2 , b_3 , b_4 , which is not composed of pure a or pure β crystals, but is a mixture of these two, which is richer in a crystals on the side bordering on pure a , and richer in β as we approach the field of pure β . Similarly we find fields composed of $a + \gamma$, $\beta + \gamma$, $\gamma + \epsilon$, $\delta + \epsilon$ and $\epsilon + \eta$.

Let us now trace the chemical changes which occur in the cooling of an alloy of a given composition. An alloy of, for example, 55 percent copper, is in the molten condition somewhere above 880° , the temperature at which it begins to solidify. Between this temperature and that represented by the dotted line, which is about 860° , β crystals begin to separate from the mother liquor. These continue to separate as the temperature drops. When the dotted line, or solidus, is reached the melt freezes completely, and the mass is composed of pure β crystals. As the mass continues to cool, β crystals begin to break down into a crystals. This change begins at about 600° . As the cooling progresses, more and more β crystals break down into a crystals. Thus we have a mixture of $a + \beta$ crystals, until we reach a temperature of 470° , at which point the β crystals break down into γ crystals. Below this temperature we find a mixture of $a + \gamma$ crystals. This condition results from very slow cooling. If, however, we take the same 55 percent alloy, cool slowly, and then heat it to some high temperature, somewhere below the initial freezing point, for example 800° , and hold it there until equilibrium conditions are attained, it will be composed of pure β crystals. If quenched quickly in water from this

temperature, the β crystals do not have time to change over into α crystals, and at ordinary temperatures the alloy retains the same crystalline structure which it had at 800° . One could, therefore, determine the strength of a pure β alloy by annealing a 55 percent alloy at 800° , or any other temperature falling within the β field, until equilibrium is reached, and then quench it rapidly; or, what is equivalent, if we quench the bar immediately after casting, we attain practically the same results.

As the alloys containing less than 50 percent copper are extremely brittle, and not used very extensively in technical work, this report covers only the α , $\alpha + \beta$, β and a very small portion of the $\beta + \gamma$ fields. $\alpha + \gamma$ does not enter into it as all quenching was done considerably above 470° —the upper limit of this field.

Materials and Apparatus

The crucibles used in this work were made from cylinders of Acheson graphite. Three sizes, measuring respectively, 4, 6, and 8 inches in diameter and 6, 8, and 10 inches in height (outside dimensions), were employed. The smallest crucible contained the melt and was placed inside the one of medium size; the reason for this will be given later. These crucibles were turned from the cylinders by placing them in a lathe and using ordinary machine tools. It must be noted, however, in passing, that graphite dulls the edges of tools very quickly, making it almost impossible to keep tools sharp. But this is not a serious handicap as the material cuts easily. These graphite crucibles were entirely satisfactory in every respect except durability. It was impossible to prevent the heat from burning away the surface of the crucibles. In most cases about twenty-five pourings were made from a single crucible, although in the lower melting alloys many more were made. Dixon crucibles were also tried but they proved unsatisfactory for this work, chiefly because they chipped easily, and furthermore they could not be adapted to the method of pouring employed here.

About 1600 grams of metal were used for one pouring. Experiments were made with amounts varying from 1500 to 2000 grams, but no advantage seemed to be gained by using more than 1600 grams.

The heating was done in a 30 k. w. electric resistance furnace. It was $34 \times 23 \times 15$ inches and was built of Queen's Run fire brick and cement. The walls were 4 inches thick—the width of a brick. The electrodes were made of Acheson graphite 2×4 inches (made up of two 2×2 inches) and extended inward through the ends of the furnace about 7 inches, with 4 inches outside the furnace walls. These electrodes were held in place by water-cooled electrode holders.¹ Fig. 2 shows a top view of the furnace. A is the brick wall, B a thick lining of siloxicon to prevent loss of heat by radiation, D the space occupied by granular carbon, C crucibles, E electrodes, and F electrode holders. A layer of siloxicon about an inch thick was also placed above and below the granular carbon.

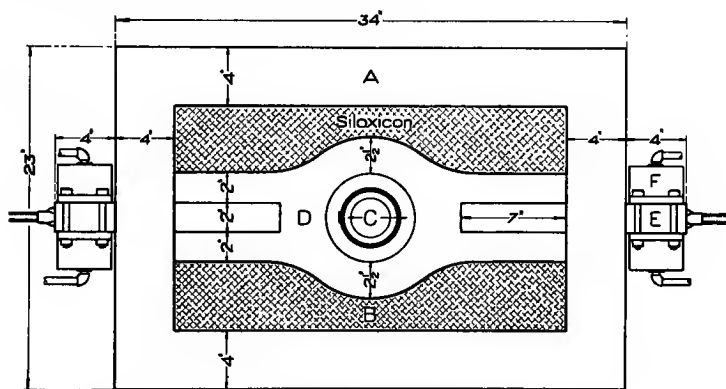


Fig. 2

The outer crucible (the medium size mentioned above) was kept stationary in the furnace, with its top very nearly on a level with the upper layer of siloxicon, so as to prevent

¹ Gillett: Jour. Phys. Chem., 15, 213 (1911)

burning away as much as possible. The smaller crucible containing the charge rested in this one, being on a level with the top. A small piece was cut from the inner edge of the outer crucible, to admit taking hold of the inner one with tongs. By this arrangement the crucible containing the charge could be removed at will, without tearing out the furnace charge.

The heating was usually begun with about 125 volts across the terminals; as the temperature rose the resistance decreased, and the voltage dropped to about 50 volts where it was held throughout the greater part of the run. This furnace could easily attain a temperature of 1200°, which was ample for this work.

The moulds¹ were made of two slabs of Acheson graphite, each 1 × 5 × 17 inches. The pattern of the casting consisted of the centrifugal sprew, $\frac{3}{4}$ inch in diameter, the test-piece ten inches in length, and the riser $1\frac{1}{4}$ inches in diameter. The test-pieces were cast to size for testing, and were composed of the test section 0.40 inch in diameter and six inches in length, and the grips at the ends 0.75 inch in diameter.

When casting test-pieces to size, the size of the riser is very important. If too small, an insufficient amount of metal is carried beyond the test-piece proper, and consequently any slag or oxide carried along in the pouring may lodge in the test-piece and render it faulty.

The moulds were made as needed. A mould could be used for about seventy-five castings. The greatest wear upon the moulds resulted from the effect of heating, which gradually burned away the outside, especially the bottom, causing the metal to run through when poured into the mould. In the preparation of the moulds, the graphite slabs were first made smooth on one side by means of a planer or shaper, so as to enable them to be clamped tightly together. This planing is usually necessary, as the slabs are generally somewhat warped when received from the factory. Most of the

¹ Shepherd and Upton: *Jour. Phys. Chem.*, 9, 441 (1905).

cutting was done by means of ordinary carpenter's gouges, but care had to be taken in making the grooves for the test section. After cutting out the grooves roughly, the smooth inside finish was most satisfactorily produced by means either of discarded safety razor blades rounded on end and made into scrapers, or short pieces of glass tubing of the proper diameter with sharp ends.

Probably the greatest difficulty encountered in this work was that of pouring. The mould was first placed in a level position, but it was impossible to fill the test-piece portion at the far end. This was due to the hot metal freezing too quickly in the bottom portion of the test-piece, and thereby leaving unfilled gaps on top. It was noticed, however, that the metal in the riser was always homogeneous and of good quality. This was, of course, filled from the bottom. Hence it seems wise to raise the far end of the mould so that the part occupied by the test-piece would fill by being pushed up the incline by the weight of the metal. This was an improvement, but it was finally found that it could only be filled satisfactorily by both inclining and heating the mould. A large box was therefore placed near the furnace and through the top of this were projected three gas muffle burners, about six inches apart. The box was covered with several sheets of asbestos. The mould, clamped tightly together was set on blocks of graphite directly over the burners and surrounded by fire bricks and sheets of asbestos. The whole apparatus was tilted so that the mould was about ten degrees from the horizontal (see Fig. 3). The mould was heated to bright redness for the higher melting alloys while a dull red was sufficient for those melting at lower temperatures.

As is well known, one of the greatest difficulties in the melting of brass is the loss of zinc by oxidation. This oxidation was cut down by the use of powdered charcoal, sodium chloride,¹ and by passing illuminating gas directly into the crucible, through an iron cover placed over it. These pre-

¹ The Brass World, Sept., 1912, page 307.

cautions were sufficient to reduce the oxidation of the zinc to a minimum, while being heated in the furnace, but the moment the crucible was uncovered for pouring, considerable oxidation occurred even before the melt could be transferred to the mould. In spite of the rapidity of pouring and the use of the centrifugal sprew, it was found that when the metal was poured from the top of the crucible small pieces of oxide were carried into the test section; and, being insoluble in the melt, they rendered the casting worthless. This difficulty was overcome by pouring from the bottom of the crucible, as in the Thermit process, thus avoiding the oxides almost entirely. A hole $\frac{3}{8}$ inch in diameter was bored in the bottom of the crucible and close to the inner edge. A graphite plug extending to the top of the crucible was fitted into the hole. A heavy arm of wood 2×3 inches \times 4 feet was screwed in a slightly slanting position to a nearby permanent support, (see Fig. 3) so as to extend just over the mouth of the mould, and a few inches above it. On the end of this arm was screwed a heavy iron plate, semi-circular in form with the lower edge projecting inward. The crucible could thus be taken from the furnace and held by means of tongs on this semi-circular support. By means of a previously made gauge-mark on the outside of crucible, the hole in the bottom could easily be placed directly over the mouth of the mould. While holding it in this position the plug could be pulled from the top, thereby allowing the metal to be poured in a continuous stream. Without this support the drawing of the plug usually jarred the crucible so much that a continuous stream could not be sent into the mould, without which it is almost impossible to get good castings with the type of mould used here. In order that the mould, after having been removed, could be placed in the proper position with respect to the crucible, two adjustable iron guards were fastened to the arm just back of the semi-circular support. One of these was arranged so as to press against the end of the mould and the other against the side. By placing the mouth of the mould directly

under the outlet of the crucible and adjusting the two guards, the mould could be removed and always replaced in the same position with respect to the crucible. However, by this method of pouring, the excess metal could not be retained in the crucible. So an asbestos trough was placed under the front end of the crucible and when the mould was filled, the remaining metal was carried into a tank of water. After each pouring, the zinc oxide formed during the pouring was scraped from the inside of the crucible before placing another charge in it.

Fig. 3 shows the general arrangement of the apparatus. A is the mould resting upon graphite blocks and held in place by the movable guards E and F. A section of the crucible

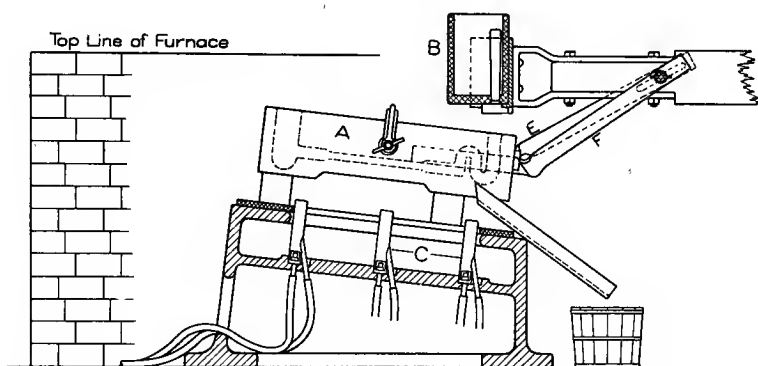


Fig. 3

B, is shown with the hole for pouring and the plug directly over the mouth of the mould. C is the frame holding the muffle burners.

After the pouring, the mould was opened quickly and the casting immediately quenched in water. As most of the castings were quenched from red heat, it was necessary to guard against bending the test-piece while removing it from the mould, especially as the metal forming the spew and riser was very much heavier than the rod itself. Hence, for quenching, a slab of graphite to which was fastened a

stationary upright strip of iron, was placed across the top of the can of water. One-half of the mould was removed, and the half containing the casting was placed in an almost vertical position on this graphite slab, being supported against the iron strip. Then by means of a suitable hook, the casting could be removed from the mould and lowered vertically into the water.

The materials used for making the test-pieces were electrolytic copper of 99.98 percent purity and pure Bertha spelter, thus avoiding the influence of even minute quantities of foreign metals. The copper which is sold in twenty-pound pigs, was sawed into two pieces and these pieces were melted in the electric furnace and recast into small ingots, or granulated by pouring into water. For this melting the largest of the crucibles previously described was packed in the furnace and the one of medium size used for the melting. The zinc, which is sold in slabs, was broken into small pieces. To avoid loss of zinc by volatilization in the subsequent work, at the beginning of this set of experiments a large quantity of 50 : 50 brass was made as a basis for starting. To this, copper could then be added to make any desired composition.¹ The excess metal from pouring and the broken test-pieces were melted over and over. In every case, in which pure copper was used, it was melted first and then the lower melting alloy, or zinc, was added.

A careful study of the pouring temperatures was made. A base metal thermocouple supplied by The Hoskins Manufacturing Company of Detroit, was used for these measurements. This couple may be placed directly in the melt. It was rather satisfactory, but cannot be considered an entire success. After using it eight or ten times it would generally break, because of corrosion, just back of the twisted ends. As nearly as could be ascertained, this corrosion occurred at that part of the couple which was at the surface of the melt or above it, rather than at the part in the melt. The tempera-

¹ Desch: Metallography, page 108.

tures were taken just as soon as the metal reached the molten state, and pouring was usually done very soon after this to avoid overheating by holding the metal too long in the furnace.

Testing

All of the tests were made on a 10,000-pound Olsen hand machine.

After sawing the metal formed by the sprew and the riser from the test-piece, it was tested as cast, except that the small fins formed along the test rod by the burning out of the graphite around the casting were filed away and the center of the piece was filed very slightly, to ensure the locality of the break.

The diameters of the test-pieces were taken at the slightly reduced areas by means of a micrometer caliper reading to thousandths of an inch. As the pieces were not perfectly circular three diameters were taken, and the average used for computing the strengths. The records of elongation were taken between five-inch lengths on the test-piece, by means of fine-pointed dividers, and read on a steel scale divided into hundredths of an inch.

The broken pieces were always examined carefully, and the general appearance, together with the character of the fracture, as seen under a hand lens, was carefully recorded. Much valuable knowledge of the interior of the pieces was thus gained. In addition, three diameters of the fractured ends were taken, from the average of which, were computed tensile strengths, based on the reduced areas. Of course, the values thus obtained are not perfectly accurate owing to the difficulty of taking accurate measurements on such broken ends. But, allowing for the error, they give us some interesting data.

In determining the value of a piece, after making the test, it was considered good if it had the proper color and homogeneity, and contained no large holes. It was called good even if it contained one or two pinholes of occluded gas.

On account of the heavy loss of zinc by volatilization

during the melting, it was impossible to prepare test-pieces of a given composition. This could be done to within 1 percent in the compositions above 65-70 percent copper, but in those of a higher zinc content, it was difficult to come quite as close. As a result, each piece had to be analyzed. Hence, the nature of the fracture determined whether a piece should be analyzed or not. And, in addition to the good pieces, only those others whose composition it seemed desirable to have, were analyzed. Copper was determined electrolytically and the zinc obtained by difference.

Results

The results of this research are given in the accompanying tables, and are presented graphically by means of curve diagrams. It was thought desirable not to present all the data taken, as this would be too cumbersome.

Table I gives a complete summary of the final results. The first column shows the copper composition of each alloy obtained by analysis. In the second column are recorded the temperatures as taken just before pouring. The third column shows the freezing temperatures for the corresponding compositions, taken directly from the freezing curve (Fig. 1). In the fourth column are tabulated the differences between the pouring temperatures and the corresponding freezing temperatures. The next column shows the ultimate tensile strengths in pounds per square inch, while in the following column are given the ultimate strengths based upon the reduced areas of the broken ends. Following this, we have the ductilities, based on five-inch lengths on the test-pieces, and in the last column the good pieces are designated by "G" and the faulty ones by "B."

Table II gives a list of the "good" pieces of the regular series.

No work was done on heat treatment.

The tensile strength curve is shown in Fig. 4. The abscissas are percentages of copper, while the ordinates are pounds per square inch. For comparison, the values of

TABLE I—Summary of tests

Percent copper	Pouring temperature	Freezing temperature	Difference	Tensile strength		Ductility	
				Original section	Fractured sections		
100	1160	1080	78	14419	—	17.2	B
—	1170	1082	88	22618	—	19.3	G
95.5	—	—	—	30053	—	17.5	G
94.0	—	—	—	25243	—	17.5	B
90.6	—	—	—	29320	85646	28.8	G
90.5	1230?	1050	180	27660	60151	—	G
90.3	—	—	—	31392	71401	30.8	G
88.5	1140	1040	100	32181	64014	24.8	G
88.2	—	—	—	29443	85189	28.0	G
87.6	1150	1040	110	30690	68461	24.4	G
86.0	—	—	—	32000	—	—	B
86.0	—	—	—	28200	—	12.5	B
85.6	—	—	—	30890	79100	24.8	G
81.3	1120	1015	105	32293	67047	22.8	B
81.3	—	—	—	32634	65930	30.8	G
81.2	—	—	—	33590	95875	—	G
80.0	—	—	—	26137	—	—	B
80.1	—	—	—	30574	—	—	G
80.5	1130	1000	130	30486	—	—	B
79.7	—	—	—	30900	57830	24.3	G
79.6	1140	1000	140	31899	64642	26.1	B
77.8	—	—	—	31199	65000	—	B
77.3	—	—	—	27560	54687	24.6	B
77.0	1210	985	225	27449	48789	24.9	B
76.1	1080	980	100	32323	51933	29.6	G
76.0	—	—	—	29100	—	—	B
75.3	1160	980	180	26311	45145	22.2	B
74.1	1220	970	250	31820	—	—	B
74.3	1200	970	230	32000	58300	—	B
73.3	1020	960	60	33955	65200	—	B
72.3	1090	960	130	31101	49563	—	G
72.0	—	—	—	24900	—	—	B
71.9	1100	960	140	34449	64600	31.4	G
70.9	1070	950	120	29138	41800	—	B
70.5	—	—	—	32300	—	—	B
70.5	—	—	—	19400	26748	11.2	B
70.3	—	—	—	26752	45368	—	G
70.2	1100	950	150	30528	—	—	G
70.2	—	—	—	28983	—	22.7	B
68.8	—	—	—	33090	48500	60.4	B
66.5	1030	920	110	34000	—	—	B
66.3	1030	920	110	36465	64262	35.6	G

TABLE I—(Continued)

Percent copper	Pouring temperature	Freezing temperature	Difference	Tensile strength		Ductility	
				Original section	Fractured sections		
65.8	1100	915	185	35200	67500	29.1	G
65.8	1070	915	155	36701	75000	31.5	B
65.2	—	915	—	35800	—	34.1	G
64.5	1020	910	110	41359	87300	—	B
63.1	1030	900	130	46559	108000	—	G
62.7	1075	893	180	47457	82250	30.8	B
62.3	1050	890	160	47715	120500	36.2	G
62.3	1030	890	140	50917	86620	31.8	B
62.3	1020	890	130	52300	89730	34.8	G
61.4	950	890	60	53043	99509	29.8	G
61.1	1000	890	110	55555	101800	25.2	G
60.9	980	890	90	56355	127990	31.6	G
60.6	1060	890	170	50149	73799	25.2	B
60.5	940	890	50	56211	103230	24.1	G
60.3	1000	890	110	57409	97153	26.0	G
59.8	1080	890	90	58139	104166	20.4	G
59.4	—	—	—	55800	135621	38.0	G
59.0	1000	890	110	56147	80117	21.0	G
58.1	950	890	60	62909	81400	—	G
57.7	960	885	75	55971	67000	—	G
57.1	1000	885	115	66910	—	—	G
57.0	950	885	65	59454	71509	9.6	G
56.7	1050	885	165	69534	93421	—	G
56.4	1030	885	145	68806	95301	14.1	G
55.7	1010	885	125	63697	—	11.4	B
55.4	1050	885	165	71193	95515	14.8	G
55.0	950	885	65	59666	96728	17.0	B
54.9	1000	880	120	62119	76504	12.8	G
54.8	1050	880	170	62555	87643	12.0	G
54.8	950	880	70	57835	74510	9.8	B
54.1	1050	880	170	68181	94458	13.6	B
53.0	980	880	100	49900	60325	9.2	G
53.0	1050	880	170	66026	81311	—	G
53.0	1040	880	160	58349	—	—	B
52.0	—	—	—	42900	—	—	B
48.1	—	—	—	10080	—	—	B
48.5	—	—	—	14000	—	—	B
47.5	—	—	—	24531	—	—	G

TABLE II—"Good" pieces in regular series

Percent copper	Pouring temperature	Freezing temperature	Difference	Tensile strength		Ductility
				Original section	Fractured sections	
100.0	1170	1082	88	22618	—	19.3
95.5	—	—	—	30053	—	17.5
90.6	—	—	—	29320	—	—
90.3	—	—	—	31392	71401	30.8
88.5	1140	1040	100	32181	64014	24.8
88.2	—	—	—	29443	85189	28.0
87.6	1150	1040	110	30690	68461	24.4
85.6	—	—	—	30890	79100	24.8
81.3	—	—	—	32634	65930	30.8
81.2	—	—	—	33590	95875	36.8
80.1	—	—	—	30574	—	—
79.7	—	—	—	30900	57830	24.3
76.1	1080	985	95	32323	57933	29.6
72.3	1090	960	130	31101	49563	—
71.9	1100	960	140	34449	64600	—
70.2	1100	950	150	30528	—	—
68.8	—	—	—	33090	48500	60.4
66.3	1030	920	110	36465	64262	35.6
65.8	1100	915	185	35200	67500	29.1
65.2	—	—	—	35800	—	34.1
63.1	1030	900	130	46559	108000	—
62.3	1020	890	130	52300	89730	34.8
62.3	1050	890	160	47715	102500	36.2
61.4	950	890	60	53045	99509	29.8
61.1	1000	890	110	55555	101800	25.2
60.9	980	890	90	56355	127990	31.6
60.5	940	890	50	56211	103230	24.1
60.3	1000	890	110	57409	97153	26.0
59.8	1080	890	190	58139	104166	20.4
59.4	—	—	—	55800	135621	38.0
59.0	1000	890	110	56147	80117	21.0
58.1	950	890	60	62909	81400	—
57.1	1000	885	115	66910	—	—
57.0	980	889	95	61754	63900	9.6
56.7	1050	885	165	69534	93421	—
56.5	1030	885	145	68806	95301	14.0
55.4	1050	885	165	71193	95515	14.8
54.9	1000	880	120	62119	76504	12.8
54.8	1050	880	170	62555	87643	12.0
53.0	1050	880	170	66026	81311	—
47.5	—	—	—	24531	—	—

Thurston and Mallet are also given on the same plate. There is a slight increase in the tenacity with the first addition of zinc, after which the values remain almost the same throughout the α field, increasing only about 5000 pounds per square inch over the range to about 66 percent copper. From that

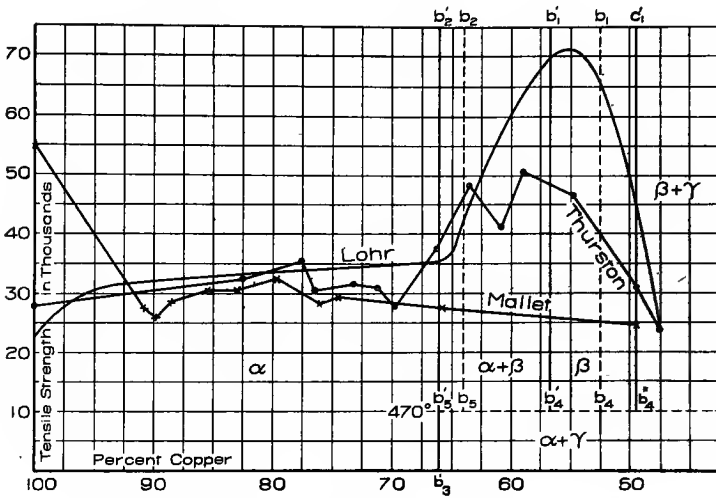


Fig. 4

point there is a very sudden increase, the values going up rapidly to a maximum at 55.4 percent copper. The values fall very gradually from that point to that of 53 percent copper, while a very sudden drop is noticed in the alloys containing from 53-47.5 percent copper. Beyond this no work was done, as these alloys are very brittle and not of very great practical use. Owing to the great number of castings made, values of close compositions were obtained, resulting in a very smooth curve.

Since the test-pieces used in this investigation were all quenched immediately after casting, it was predicted that the lines b_2b_6 , b_1b_4 and c_1b_4 , marking respectively the boundaries between the α , $\alpha + \beta$ and pure β fields, would be somewhat changed from the positions which they occupy on the equilibrium diagram (Fig. 1). In order to determine the extent

of these changes, a series of specimens taken from the ends of various test-pieces were examined microscopically and photographed. The dendritic structure of the α crystals referred to by Shepherd,¹ was seen very plainly in specimens containing 81.3, 74.6, 71.9, and 66.3 percent of copper. However, the 65.8 percent alloy showed small areas of β crystals scattered through the great mass of α crystals. This shows that the field of pure α ends at about 66 percent copper. Comparison with the diagram will show this position to be somewhat to the left of the line b_2b_3 , as obtained under equilibrium conditions. In a similar manner, we find the line b_1b_4 moved to the left. The 55.4 percent alloy was composed entirely of pure β , while the 57.1 percent alloy showed a considerable mixture of α crystals, indicating very plainly that pure β extends almost to 57.0 percent copper. On the other hand, the position of the line c_1b_4 was found to change somewhat to the right of that shown on the equilibrium diagram. The 53.0 percent alloy consisted entirely of pure β , whereas the one containing 47.5 percent copper was shown to consist of about three-fourths β , distributed through the γ metal. This indicates that pure β must cease to exist at about 49 or 50 percent copper. Remembering that the castings used in this work were quenched at about 700°–800°, and before equilibrium was reached, we can account very satisfactorily for the new positions of these boundary lines. In the several figures in this paper the positions of the boundary lines of the different phases as found here, are contrasted with their positions on the equilibrium diagram. The latter are represented by dotted lines, while the heavy lines show the boundaries obtained in this work.

If we compare the tensile strength curve with the positions of the boundary lines here established, we find a very close relationship. Throughout the α field there is only a slight change in the tensile strengths. At about 66 percent copper, where the β crystals begin to appear, the strengths

¹ Jour. Phys. Chem., 8, 427 (1904).

begin to increase, and continue to increase throughout the range of the metal composed of $\alpha + \beta$ crystals. The maximum strength is found to lie wholly in the β field. As we approach the γ field the strengths fall rapidly, until at 47.5 percent copper where the amount of β is small, the tenacity is only about 25,000 pounds per square inch.

Let us now compare the results of this paper with those of Mallet and Thurston. Mallet's strength of pure copper is hardly comparable here, as his test-pieces were prisms 0.25 inch square. It will be referred to later. His results between 90 and 75 percent copper agree well with Thurston's, but he seems to have neglected the section of greatest change in strengths, as his work includes no tests between 66 and 49 percent copper. Thurston's curve is of the same general form as that obtained by the writer, but much more irregular. For compositions around 70 percent copper, and for those containing less than 63 percent copper his values are considerably lower. His maximum is at about 58 percent copper.

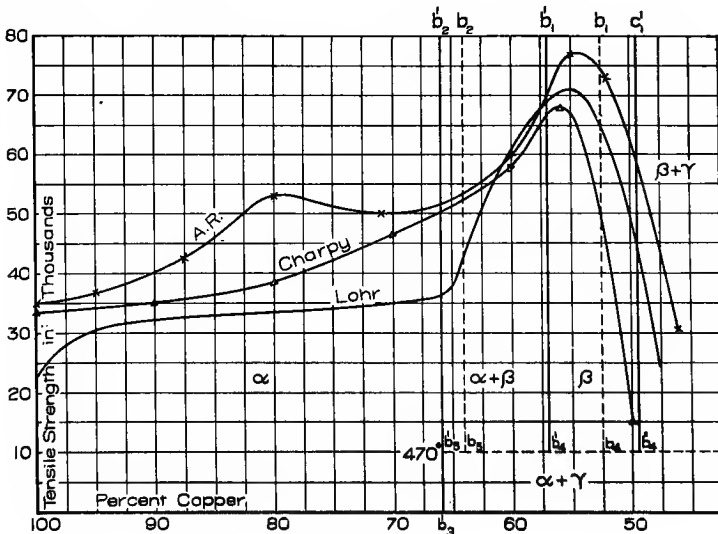


Fig. 5

In Fig. 5, comparison has been made with the work of

Charpy on annealed brasses, and with that of the Alloys Research Committee¹ on worked rods. As would be expected, the tensile strengths of worked metal are greater than those of cast metal throughout the greater part of the series. This is due, of course, to the decrease in the grain size brought about by working the metal. On the other hand, for annealed brasses one would predict tensile strengths lower than those given by castings without heat treatment. This decrease in strength should result from larger crystals due to annealing. But Charpy's results show greater strengths over the whole of the α field and a part of the $\alpha + \beta$ fields. This must be very largely due, therefore, to the small size of the test-pieces which he used. These pieces were 5 mm in diameter, and consequently on quenching, would cool very rapidly, thereby reducing the grain size, and giving high tensile strengths. The presence of traces of other metals may also have had an effect in increasing the strengths.

The small size of the test-pieces, and therefore the small grain size, will also probably account for the abnormally high value for cast copper obtained by Mallet, as the prisms used in his tests were 0.25 inch square.

In connection with this it is also interesting to notice the very high tensile strengths, based on the reduced areas as shown in Table I. In the region of 60 percent copper these strengths are considerably over 100,000 pounds per square inch, in one case (alloy 59.4 percent copper) attaining a value of 137,000 pounds per square inch. This value is 40 percent higher than the maximum obtained by the Alloys Research Committee with worked metal. As this is practically the strength of the alloy at the time of break, it is in reality the breaking strength of "drawn" brass and shows the ultimate possibility of obtaining such values for metal thus worked. In view of this fact, and noting that extruded zinc² with a tensile strength of 23,000 pounds per square inch,

¹ Proceedings of Mech. Engineers, Parts 1 and 2, 31 (1897).

² Jour. Franklin Inst., 172, 558 (1911).

and electrolytic copper¹ of 68,000 pounds per square inch have recently been obtained, some interesting possibilities for future high tensile strengths are suggested.

In casting these alloys, little trouble was experienced in obtaining good homogeneous test pieces above 80 percent copper, but from 65–80 percent copper it was exceedingly difficult. The greatest difficulty was that of porosity.

Dozens of castings were made, perfect in external appearance, only to show upon breaking, a thin solid homogeneous outer crust or shell, within which was an area of porosity, varying according to the conditions under which the metal was melted and poured. The melting was largely done under illuminating gas which, for the purpose of preventing oxidation of the zinc, was led through a perforated cover into the top of the crucible. On this account, it was thought that perhaps the molten metal had absorbed gases, which it could not force out when quenched immediately after casting. Therefore, experiments were made, keeping all other conditions the same, in which granulated charcoal, sodium chloride, and illuminating gas, respectively, were used as a protection for the melt. The gas was used in the ordinary manner—that of leading it into the top of the crucible. And in a few cases it was led through a carbon tube directly into the melt, and distributed through it by stirring with the tube carrying the gas. Under each of these conditions, several pieces were quenched immediately after they were removed from the mould; others were quenched after they had been allowed to remain in the air in the open mould for about three minutes; and still others were allowed to cool in the air. In almost every case the pieces allowed to cool in the air showed, upon breaking, good solid homogeneous metal, free from porosity. There were, however, a few instances in which slight traces of porosity could be noted even in these. But while the porosity was thus almost entirely prevented, the crystallization was allowed to take

¹ Bennett: *Jour. Phys. Chem.*, **16**, 294 (1912).

place slowly, thus giving large crystals and a consequent reduction in strength. In every case the metal was porous in the pieces quenched at once. This was more marked in those pieces in which gas had been led into the melt. The best results were obtained in the cases in which quenching was done about three minutes after the metal was poured and the mould opened. Even when gas was used, solid homogeneous metal was obtained, when the pieces were quenched under these conditions.

In every instance, when the broken ends showed porosity, a solid shell of metal was noticed on the outside of the piece, and also in many instances there was a distinct break, or pipe, in the center. In view of these experiments, a possible explanation is that the dissolved gases have time to escape when the metal is allowed to cool entirely in the air, or is allowed to remain in the air for a few minutes before quenching, whereas when the pieces are quenched at once the sudden cooling causes a thin shell of metal to form on the outside, thus preventing the gases in the interior from escaping.

As we pass from 65 percent copper toward a lesser copper content, a very different kind of metal is noted. This is the range of the mixture of α and β crystals. This was decidedly the easiest brass to cast, as almost every casting was solid and gave a good break. There was, however, a slight tendency toward the formation of holes lined with a bright yellow covering; but these were few in number. The fractures were mostly V shaped or oblique to the main axis of the piece. From 60–63 percent copper there was noticed quite a tendency to “neck.” From 57 percent copper over the range of the β field we find a very hard metal, with little ductility. In spite of the short time for crystal growth, the crystal structure was large as revealed by the ragged, irregular fractures. Below 50 percent copper the crystalline structure was pronounced and very well defined.

The ductility curve is shown in Fig. 6. This rises

gradually with the addition of zinc and attains a maximum¹ at about 65 percent copper. It drops very suddenly at about 60 and then falls off gradually almost to zero at 47.5 percent copper. The maximum here shown differs somewhat from that obtained by other investigators, as both Thurston with castings and Charpy with annealed brasses found the maximum ductility to be at about 70 percent copper. This change in the maximum is evidently due to the method of cooling employed in this work. Under equilibrium conditions, as seen from the curves of the investigators mentioned above,

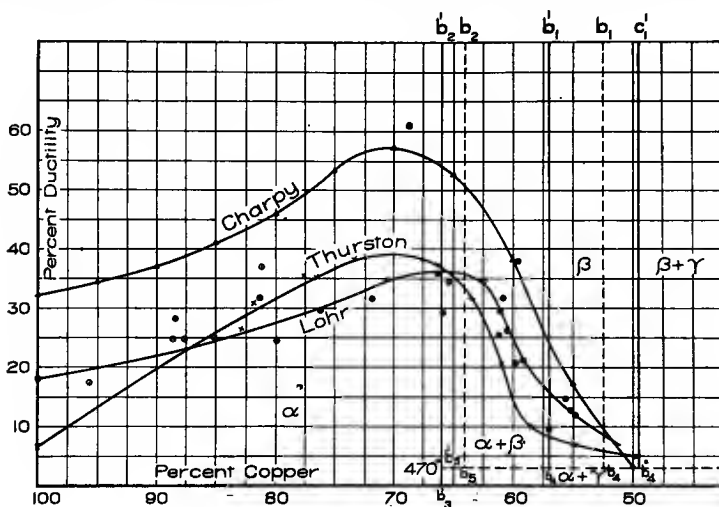


Fig. 6

the maximum falls just within the limits of pure α . Beyond that, the $\alpha + \beta$ crystals would break down into $\alpha + \gamma$ at the lower temperatures. The introduction of γ might possibly result in brittleness and decreased ductility, although this is not certain. If the γ metal is distributed through the α in a highly agglomerated condition, it undoubtedly would decrease the strength, whereas there is

¹ One 68.8 percent brass gave the remarkable elongation of 60.4 percent., but this could not be duplicated.

some question as to the effect of very finely divided γ distributed through the α metal. On the other hand, by the method of rapid cooling employed here, it is quite likely that only sufficient β crystals were carried over into α to increase the ductility and thus to throw the maximum to about 66 percent copper. This seems quite probable in view of the microscopic results previously mentioned. Here it was shown that β began to appear at about 66 percent copper. Pure β is very low in ductility but it appears that a mixture of $\alpha + \beta$, with a preponderance of α , gives the highest ductility, when cooled quickly after casting.

The effect of the temperatures of pouring upon the strength of the brasses may best be noted by an inspection of Table II. A great majority of the "good" pieces were poured at temperatures somewhere between 100° and 200° above the liquidus. In a few cases, with the temperatures less than 100° above the liquidus, good castings were obtained, but generally the metal was too viscous to be handled easily, and to fill the mould properly. However, it was absolutely impossible to obtain good test-pieces with the pouring temperature more than 200° above the liquidus. In every case the castings were of good external appearance, but contained numerous black spots of porous material presumably copper oxide. This was more noticeable as the copper content increased. In many cases, those pieces cast from temperatures more than 200° above the liquidus showed less than a fourth of the strength which their compositions should have given.

It was impossible to limit the pouring temperatures to a closer range than 100° , as it will be noticed by referring to Column 4 of Table II, that frequently, castings of about the same compositions gave practically the same strengths, with temperatures as much as 50° apart.

In general, then, it may be said that brasses with the highest strengths can be obtained by having the temperature of pouring within the range of 100° C to 200° C above the liquidus.

Conclusions

The following conclusions may be drawn from the results of this work:

1. A study of the tensile strengths of the cast brasses containing 47.5–100 percent copper has been made.
2. The α brasses give almost a constant value for the tensile strengths.
3. The maximum tensile strength occurs in the neighborhood of a 55 percent copper alloy, and its value is about 71,000 pounds per square inch.
4. The β alloys give the highest tensile strengths.
5. The maximum strength does not occur on a boundary curve.
6. The variations in the tensile strengths agree very closely with the constitution of the alloys, as proven by the microscopic study.
7. A tensile strength of 137,000 pounds per square inch, as taken from the fractured ends, has been obtained.
8. A maximum ductility of about 36 percent elongation has been obtained regularly. One piece, however, showed an elongation of 60.4 percent, but could not be duplicated.
9. It is possible to obtain a cast brass having an ultimate tensile strength of 71,000 pounds per square inch, and an ultimate elongation of 14.8 percent; or, a brass having an ultimate tensile strength of over 36,000 pounds per square inch and an ultimate elongation of 35.6 percent.
10. A method for continuous pouring of metal has been devised.
11. The effect of temperatures of pouring has been investigated.

This work was suggested by Professor Bancroft, and has been carried out under his direction. This opportunity is taken to thank him most heartily for his continual kindly interest in the work, and for the many helpful suggestions offered during its progress.

Thanks are also extended to Mr. C. A. Scharschu for

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*Cornell University,
May, 1912*

